Experimental Verification of a Horizontal-Refraction Technique Using North Pacific Acoustic Laboratory Data

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LONG-TERM GOALS

To estimate a long-period (weeks-to-months) time-variation of horizontal-refraction-angles (HRA) of sound signals propagating over long range and to evaluate the usefulness of HRA for remote sensing of meso-to-global-scale ocean inner structure.

To estimate a short-period (hours-to-days) variation of HRA, to estimate the effects of sound scattering by internal waves, and to evaluate possible reduction of corresponding HRA errors by time averaging.

To calculate statistical characteristics of acoustic mode amplitudes using experimental data and to compare the results obtained with theoretical estimates.

OBJECTIVES

To study the feasibility of using HRA for estimation of the ocean inner structure on meso-to-global scales by processing North Pacific Acoustic Laboratory (NPAL) data obtained in the long range propagation experiments with the use of Kauai- and Pioneer sources.

To study the statistical characteristics of acoustic mode amplitudes at low frequencies and to evaluate HRA.

To verify the theory of propagation of low-frequency acoustic signals through an internal wave field and to investigate the feasibility of an appropriate scheme of comprehensive acoustic tomography of internal waves.

APPROACH

Two different approaches were applied for retrieval of HRA. The first approach is based on the modal representation of the low-frequency acoustic field. Let us assume that there is a set of hydrophones located at points $(x_\alpha, y_\alpha, z_\alpha)$. This set combines hydrophones belonging to all five vertical line arrays (VLA). The profiles of acoustic modes are given by $u_m(z,\omega)$, and the corresponding propagation

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14. ABSTRACT
To estimate a long-period (weeks-to-months) time-variation of horizontal-refraction-angles (HRA) of sound signals propagating over long range and to evaluate the usefulness of HRA for remote sensing of meso-to-global-scale ocean inner structure. To estimate a short-period (hours-to-days) variation of HRA, to estimate the effects of sound scattering by internal waves, and to evaluate possible reduction of corresponding HRA errors by time averaging. To calculate statistical characteristics of acoustic mode amplitudes using experimental data and to compare the results obtained with theoretical estimates.

15. SUBJECT TERMS

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constants are $\xi_m(\omega)$. The incident acoustic field is assumed to arrive from different horizontal directions characterized by k_y-components of the wave number which are perpendicular to the propagation direction. Using modal approach, we can represent the acoustic field as:

$$p_\alpha(\omega_i) = \sum_{m,k_y} u_m(z_\alpha, \omega_i)\exp\left(i\xi_m(\omega_i)x_\alpha + ik_y y_\alpha\right)A_m(\omega_i, k_y)$$

The resulting set of linear equations with respect to unknown A_m is solved by minimizing the difference between the right- and left-hand sides of these equations. It is also assumed that the oceanic inhomogeneities result in redistribution of the energy between acoustic modes keeping the total energy approximately constant. This condition stabilizes the numerical solution. The value of the energy constant was determined by using trials and errors. The solution was calculated for relatively narrow frequency bands (with a width of a fraction of Hz). Then, the values of interest (e.g., mode amplitudes) were averaged over all frequency bands. Solution of the problem was repeated for different values of HRA corresponding to the center of a bundle of incident horizontal rays. The pressure reduction coefficient C_{dP} was defined as a relative difference between the acoustic pressure and the superposition of modes determined above. For each HRA, C_{dP} was calculated. An example of dependence of C_{dP} on HRA is shown in Fig. 1. A true arrival angle should correspond to a minimum value of C_{dP}.

In the second approach, HRA is calculated by a standard beamforming technique using data recorded by two hydrophones located at approximately the same depth and belonging to two VLA. (For VLA 5, we only use data recorded by those hydrophones whose depth was approximately the same as those for VLA 1 - 4.) For a given pair of VLA (e.g., VLA 3 and 4), this approach results in 20 values of HRA. We omitted those values of HRA which are greater than 5 degrees or are imaginary. Then, the remaining values of HRA are used to calculate the mean value and standard deviation of HRA. These mean value and standard deviation are calculated for all possible pairs of VLA: 1 and 2, 1 and 3, 3 and 4, etc.

WORK COMPLETED

Several computer codes for accomplishing both approaches were developed. The processing included assimilation of the coordinates of the hydrophones and their time corrections.

In the first approach, a set of acoustic modes was calculated for all frequencies, and the matrix of the corresponding linear set was computed. The inversion procedure included diagonalization of this matrix, and a solution of a non-linear equation determining the energy regularization parameter. The inversion algorithm depends on a significant number of different parameters such as a total number of modes, width of the frequency interval, angular width of the arriving bundle of horizontal rays, etc. Different combinations of these parameters were tried for inversion. However, the results obtained appeared to be similar. Finally, some optimal sets were chosen.

Numerical implementation of the second approach is straightforward.

RESULTS

The two approaches described above were applied to analysis of all available acoustic data from the NPAL URL, written in *.vla and *.dmd files. These data were recorded during the year days 500 – 505. Fig. 1 presents an example of the calculated dependence of the C_{dP} on HRA.

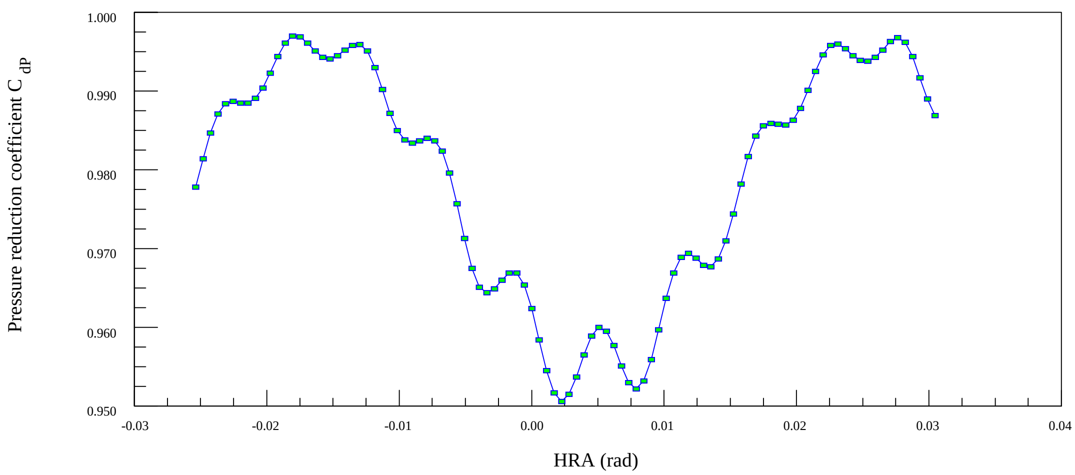

Fig.1. An example of dependency of Pressure Reduction Coefficient C_{dP} on HRA.

Minimum at $2.5 \cdot 10^{-3}$ rad is interpreted as a true value of HRA. The dependence of such obtained values of HRA on time (starting from the year day 500) is shown in Fig.2. Similar dependence of HRA on the year day was obtained by the second approach.

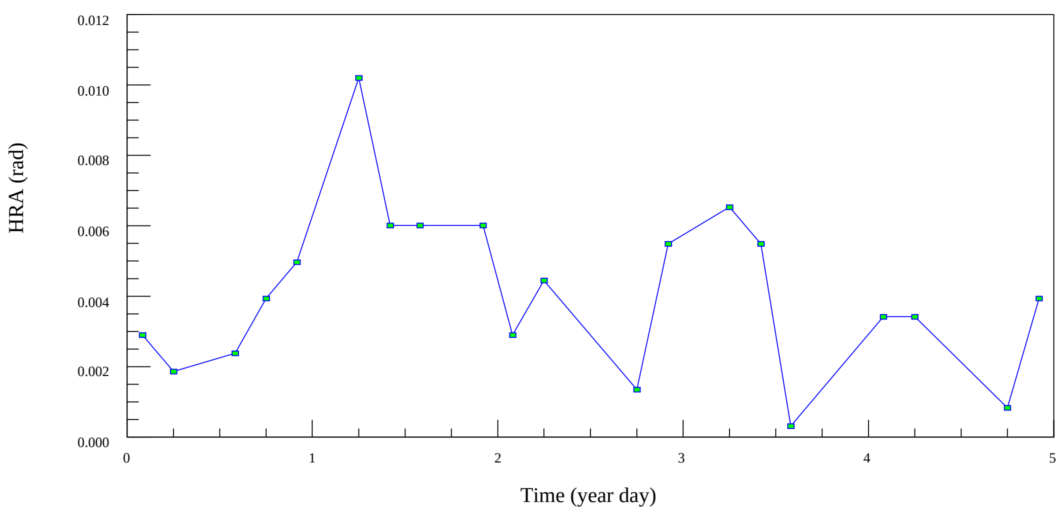

Fig. 2. Time dependence of HRA (starting from year day 500).

It seems worthwhile to calculate this dependence over a longer period of time in order to make some geophysical conclusions.

A modal content of the received signal averaged over all frequencies is shown in Fig. 3. It is clear that there is a tendency of generation of higher modes.

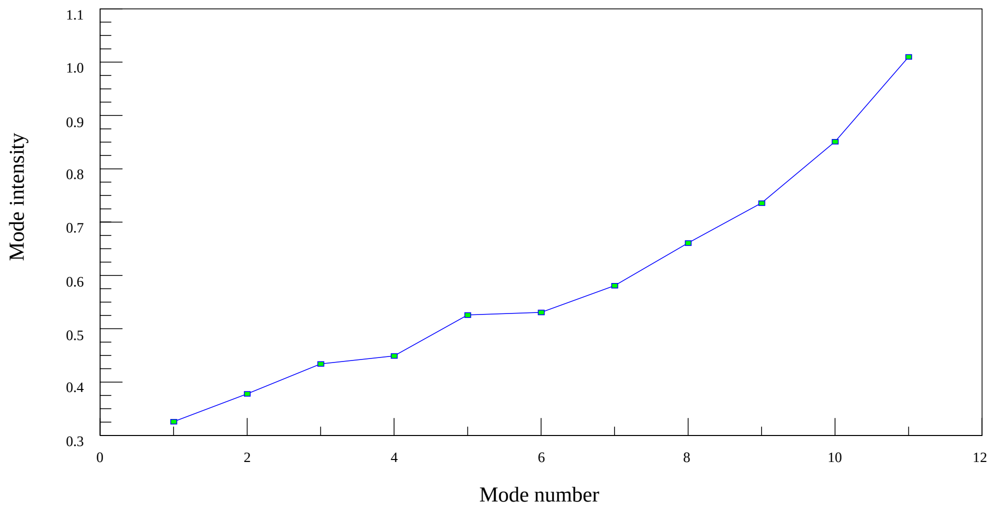

Fig. 3. Modal content (averaged over frequency) of the received signal

An example of processing *.dmd files using the second approach is shown in Fig. 4. It demonstrates the evolution of the HRA and its variance indicated by vertical bars on much shorter time scale. Data recorded by VLA 1 and 4 were used to obtain Fig. 4 (the starting time of the signal was the year day 500.781). The acoustic signal in this case is, apparently, due to a moving vessel. Using Fig. 4, we determined the angular speed of the vessel as equal to 0.245 degrees/min. If the vessel were 50 nm from VLA, its transverse speed would be 13 kn.

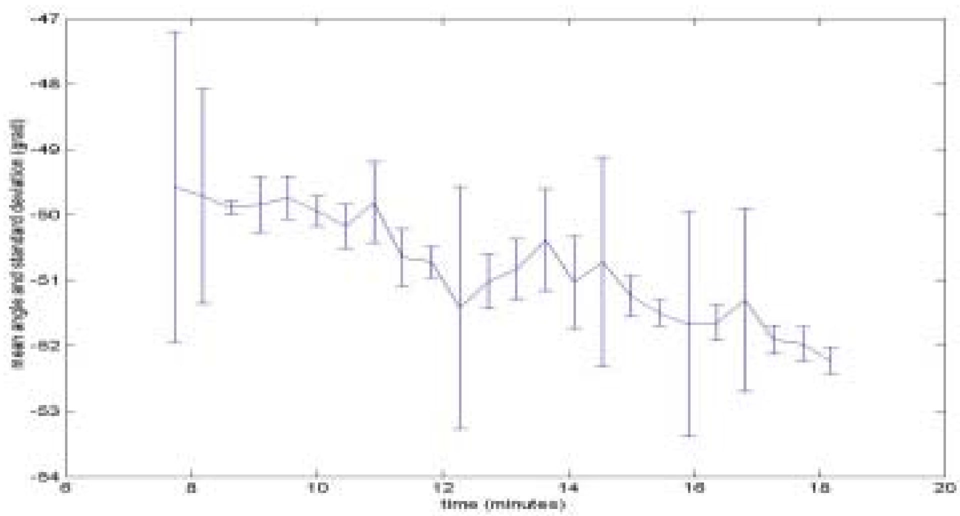

Fig. 4. Time dependence of HRA obtained by processing *.dmd files.

IMPLICATIONS

HRA characterizes the horizontal oceanic inhomogeneities on global scales. Measurements of temporal evolution of HRA can give a powerful tool for remote sensing of the ocean inner structure and corresponding dynamic processes.

PUBLICATIONS

A. Voronovich, V. Ostashev, and NPAL group. Horizontal refraction of acoustic signals retrieved from NPAL horizontal array. JASA, vol. 109, Pt. 2, p. 2385, 2001.